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Update on Mechanical Analysis of Monolithic Fuel Plates

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UPDATE ON MECHANICAL ANALYSIS OF MONOLITHIC FUEL PLATES

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ABSTRACT

Results on the relative bond strength of the fuel-clad interface in monolithic fuel plates have been presented at previous RRFM conferences. An understanding of mechanical properties of the fuel, cladding, and fuel / cladding interface has been identified as an important area of investigation and quantification for qualification of monolithic fuel forms. Significant progress has been made in the area of mechanical analysis of the monolithic fuel plates, including mechanical property determination of fuel foils, cladding processed by both hot isostatic pressing and friction bonding, and the fuel-clad composite. In addition, mechanical analysis of fabrication induced residual stress has been initiated, along with a study to address how such stress can be relieved prior to irradiation. Results of destructive examinations and mechanical tests are presented along with analysis and supporting conclusions. A brief discussion of alternative non-destructive evaluation techniques to quantify not only bond quality, but also bond integrity and strength, will also be provided. These are all necessary steps to link out-of-pile observations as a function of fabrication with in-pile behaviours.

1. Introduction

The overall goal of the Reduced Enrichment for Research and Test Reactors (RERTR) program has been to develop fuels for nuclear research and test reactors that allow effective conversion from highly enriched uranium (HEU) to low enriched uranium thereby reducing the threat of nuclear proliferation worldwide [1]. Mechanical properties of the fuel have a secondary impact on fuel behavior in terms of irradiation behavior. However, mechanical properties of the fuel are extremely important for overall plate properties. Limited data exists on the property-processing-structure relationship of metallic uranium monolithic fuel foils. Most of the available literature involving properties, specifically for U-Mo alloys, were produced in the 1950s and 60s, although processing methods and microstructural characteristics of alloys in these investigations were significantly different than those of interest for the RERTR program [2-4].

Characteristics of the monolithic fuel, both in terms of microstructure and properties, are extremely important to a successful fuel plate irradiation. Two methods are currently being aggressively investigated to encapsulate the monolithic fuel foils in 6061-T6 aluminum alloy cladding: hot isostatic pressing (HIP) and friction bonding (FB) [5]. Both of these methods can impose a significant amount of stress on the fuel foil, HIP thermally and FB mechanically, in addition to creating residual stress in the fabricated plate leading to delamination before irradiation, and significantly altering the mechanical properties of the precipitate hardened aluminium alloy used as cladding. Therefore, the monolithic fuel must have optimum characteristics to handle the thermally and mechanically induced stresses during plate fabrication and a sufficient understanding of stress behaviour on the plate composite must be gained, so that detrimental defects are not introduced prior to irradiation.

An example of the impact processing has on the monolithic foils is provided in Fig. 1. The ultrasonic photographs in the figure show a foil that has clearly been affected by the process (left) and one that has not been affected (right). Both foils were fabricated employing the friction bonding process, using the same process parameters and fabricated in the same assembly, i.e. one assembly contained two mini-foils. Clearly, there are differences in the material properties. There appears to be a clean fracture surface at the bottom right corner of the photograph on the left, suggesting that a concentration of impurities, most likely carbides, are present in this area. These “stringers” are unable to accommodate the large processing loads of friction bonding, and fracture occurs. In addition, along the upper edge of the foil on the left small, high aspect ratio pieces of fuel have been removed and re-distributed away from the fuel zone. It is believed that casting and quenching small lots of material results in a finer grains and less homogeneous microstructure than that obtained from casting, and ultimately slower cooling, of larger lots of material, i.e. that more characteristic of a large scale fabrication campaign. Furthermore, warm rolling the finer grained, less homogeneous microstructure will result in high aspect ratio grains, i.e. increased length to reduced width, which results in exceptional mechanical properties in the longitudinal direction and reduced mechanical properties in the transverse direction. Once again, the fuel foil in the photograph on the left was unable to accommodate the lateral loads associated with the friction bonding process, while such defects are rarely ever observed in the longitudinal direction.

Thus, the current update will provide results of studies that are underway and future plans to investigate the mechanical properties of the fuel alloys and cladding material, processing-parameter relationships, composite behaviour and residual stresses induced by friction bonding.

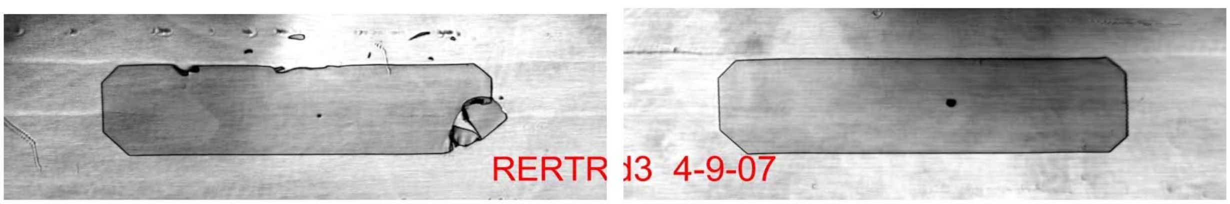

Fig 1: Ultrasonic scans of fuel plates fabricated by FSW with a flawed HEU-10Mo foil (left) and uniform HEU-10Mo foil (right).

2. Experimental Methods and Materials

1.1 Foil Preparation

Monolithic foil alloys of depleted uranium and ten weight percent (nominal) molybdenum were investigated. A small scale arc melting and casting method was employed to homogenize and fabricate the DU-10Mo coupons. Background on this method along with details relating to the preparation of monolithic foils from the coupons, can be found in Ref. 6. Annealing treatments were performed after rolling with varying temperature and time. Once foils were prepared, dog-bone tensile specimens were prepared employing a hardened carbon steel punch and die set. Scanning electron microscopy (SEM) was used to evaluate the fracture surface of failed specimens.

1.2 Cladding Preparation

Effects of friction bonding applied load on the mechanical properties of aluminium alloy 6061 cladding were investigated. Two pieces of commercial 6061-T6 aluminium alloy, each 0.914 mm thick, were used for each experiment. The alloy had a typical elongated grain structure in the rolling direction with an approximate area per grain of approximately 614 μm^2. Each aluminium alloy workpiece, both for the top and bottom sheets, measured 77.2 cm long by 7.94 cm wide. A single pass was made across the two sheets of aluminium to bond them together, on one side only. Dog-bone tensile test specimens were prepared similarly to the method discussed in Section 2.1. Thickness of each specimen varied along the length of the test piece, but was nominally 1.56 ± 0.01 mm. Specimens were produced along the length of the bond, parallel with the bond direction (stir-zone), so that a total of 6-8 tensile specimens were obtained. Note that specimens represent properties under the tool pin in the current experimental configuration.

1.3 Tensile Tests

Specimens were subjected to tensile loading employing an Instron 3366 universal testing machine. All tensile tests were conducted at room temperature with a strain rate of 0.5 mm•min^{-1}. Engineering stress (σ) – engineering strain (ε) diagrams were employed to obtain mechanical property information.

3. Results and Discussion

Results for the tensile tests performed on the DU-10Mo monolithic fuel foils are provided in Table 1. Foils were subjected to two different annealing temperatures and three different annealing times. Results in Table 1 show that the annealing time has significant effect on yield strength, elastic modulus and ultimate tensile strength. There is only a minor dependence upon annealing temperature. Foils were found to fail in three different modes, a ductile mode, a transgranular mode, and a mixed mode, examples of which are shown in Figure 2. The failure mode is not dependent upon the annealing condition employed, but is rather more dependent on impurity concentration, i.e. carbon, nitrogen and oxygen. Samples that failed in an intergranular mode had relatively low concentrations of impurities (50 μg•g^{-1} C, <3 μg•g^{-1} N and 45 μg•g^{-1} O), while those that failed in a ductile mode had large concentrations of impurities (>250 μg•g^{-1} C, >9 μg•g^{-1} N and >100 μg•g^{-1} O). Samples that failed in a mixed mode manner had impurity concentrations bracketed by the previously listed numbers, with the mostly ductile mixed mode concentrations being closer to that observed for the purely ductile failure mode. The dependence upon impurity concentration rather than annealing parameters is surprising and somewhat unexpected, especially based on the trends observed. It is important to point out that these observations are based on single foils, and reproducibility along with supporting experiments, have yet to be performed.

Annealing Temperature (^{o}C) / Time (min)	**Yield strength, σ_y (MPa)**	**Elastic Modulus, *E* (GPa)**	**Ultimate Tensile Strength, *UTS* (MPa)**	**Failure mode**
650 / 30	741 ± 21	60 ± 3	745 ± 19	Mixed mode
650 / 60	783 ± 23	65 ± 2	783 ± 21	Ductile dimple
650 / 120	814 ± 27	70 ± 3	828 ± 21	Intergranular
675 / 60	810 ± 77	69 ± 6	815 ± 76	Ductile dimple
675 / 120	829 ± 47	71 ± 6	831 ± 47	Mixed mode; mostly ductile

Tab 1: Mechanical properties of DU-10Mo foils as a function of annealing temperature and time

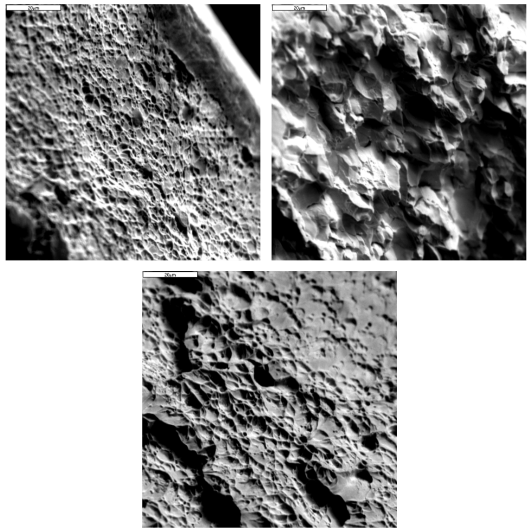

Fig 2: Fracture surfaces of tensile test specimens showing a ductile dimple failure mode (top left), an intergranular failure mode (top right) and a mixed mode (bottom)

Results of the tensile tests are summarized in Table 2 for 0.2% offset yield strength (σ_y), modulus of elasticity (*E*), ultimate tensile strength (*UTS*) and percent of elongation (e_f). Observation of the 0.2% offset yield strength shows that yield strength slightly increased as a function of applied load for single bond passes made on one side of two aluminium alloy sheets. However, yield strengths obtained for all four loads investigated are well below the base material value (271 MPa). The decrease in the 0.2% offset yield strength compared to the base material is attributed to both the loss of the strengthening precipitates that are dissolved into the aluminum matrix during the temperature increase caused by the process, and to the reduction of pre-existing dislocations in the parent material [7].

Observation of the modulus of elasticity results reveals that all values obtained are lower than those obtained for the base material (81 GPa). This observation is attributed to the relative thinness of the base material compared to the thickness of the samples tested, i.e. ~two times thicker than the base material.

Ultimate tensile strength results show similar trends to those observed for the 0.2% offset yield strength. Mainly, the *UTS* increased with increased applied load, but the experimental values are significantly lower than the theoretical values or those obtained for the base material (327 MPa). The *UTS* is observed to decrease 35% for an applied load of 62.3 kN and 38% for an applied load of 35.6 kN. This loss in tensile strength would be expected to increase for multiple bond passes made over the assembly and bond passes made on both sides of the assembly, as is the case for fabrication of the fuel plates.

One of the largest effects of the friction bonding application is on the percent of elongation of the test specimens. The percent of elongation is significantly higher than the theoretical value (~114%), while the increase in percent of elongation is moderately higher than that obtained for the base material (~40%). The percent of elongation appears to be independent of the applied load of the bond pass. Many FSW tensile test specimens reported in literature contain microstructures from the different processing zones, i.e. nugget, HAZ and TMAZ. In the current investigations, the specimens were taken from the processed area under the tool pin, so that the microstructure is relatively homogeneous. Therefore, the tensile test specimens contained only fully recrystallized grains, resulting in the significant increase in material ductility. Minimal differences were observed between the samples in the average area per grain under the pin, suggesting that there should be minimal differences in the percent of elongation, as is the trend observed. Similar observations in the stir zone have been made in other studies with mini tensile specimens [8,9].

Process Load (kN)	Yield strength, σ_y (MPa)	Elastic Modulus, E (GPa)	Ultimate Tensile Strength, UTS (MPa)	Elongation, e_f (%)
35.6	167 ± 4	66 ± 6	255 ± 4	25 ± 2
44.5	170 ± 4	66 ± 5	264 ± 5	26 ± 1
53.4	171 ± 4	72 ± 9	273 ± 4	24 ± 3
62.3	177 ± 5	65 ± 4	275 ± 4	24 ± 4

Tab 2: Mechanical properties of friction bonded AA6061 cladding as a function of process load

4. Future Plans for Mechanical Analysis

Future plans for mechanical analysis include residual stress analysis of both friction bonded and hot-isostatic pressed fuel plates. This will be accomplished by using a combination of a modified Sachs boring-out method, a deflection method and a Treuting-Read method. In addition, composite tensile test specimens will be tested to evaluate overall structural properties of the fuel plates. Combination of these tests, along with results presented, will offer an acceptable baseline for beginning of life properties to be evaluated against irradiated samples.

5. Conclusions

Mechanical properties of monolithic fuel and aluminium cladding processed by friction bonding have been presented. Properties of the fuel appear to be more sensitive to impurity concentration rather than annealing conditions. Properties of the aluminium cladding are sensitive to the applied load used during the friction bonding process. Future plans for mechanical analysis were discussed.

6. Acknowledgements

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